Competency 1.2 **Nuclear safety system personnel shall demonstrate a working level knowledge of the various types of radiation interactions with matter.**

1. SUPPORTING KNOWLEDGE AND/OR SKILLS

a. Describe the interactions of the following with matter:
- Alpha particle
- Beta particle
- Positron
- Neutron

b. Describe the following ways that gamma radiation interacts with matter:
- Compton scattering
- Photoelectric effect
- Pair production

2. SUMMARY

A knowledge of the mechanisms by which ionizing radiations interact with matter is fundamental to an understanding of specific radiation topics such as instrumentation, dosimetry, and shielding. Recall that the basic building block of matter is the atom, which consists of a nucleus, a positively charged central core containing protons and (with one exception) neutrons, surrounded by orbiting electrons. In a neutral atom, each electron supplies a negative charge to counter the positive charge(s) found within the nucleus. Ionizing radiations--those radiations that possess sufficient energy to eject electrons from neutral atoms--include alpha particles, beta particles, gamma rays, x-rays, and neutrons. These radiations transfer energy to matter via interactions with the atom's constituent parts.

An alpha particle (α) is a positively charged radiation emitted by several commonly encountered radionuclides at DOE facilities. It is composed of two neutrons and two protons grouped together with the outer electrons removed; therefore, it is identical to a helium nucleus. It is the least penetrating ionizing radiation--a sheet of paper or small amount of air serves as an effective shield. It is not harmful to humans unless the alpha-emitting substance enters the body through the typical inhalation or ingestion pathways.

A beta particle (β) is another elementary radiation emitted during radioactive decay. Beta particles are essentially high-speed electrons formed in the nucleus in one of two ways. The conversion of a neutron into a proton results in the emission of a negatively charged beta particle (β^-). Conversely, a proton can be converted into a neutron, resulting in the ejection of a positively charged beta particle (β^+). These beta particles are referred to as positrons. Beta radiation constitutes both an external hazard (as in the case of skin burns) and an internal hazard if inhaled or ingested. Typical shielding materials for beta particles consist of plastic, glass, and thin sheets of metal.

A gamma ray (γ) is a high-energy, short-wavelength electromagnetic radiation having no charge or mass. Gamma emission frequently follows alpha and beta decay and is always associated with the fission process. Gamma rays are highly penetrating radiations that travel indefinite distances in matter. This radiation type is best attenuated through the use of dense (high Z) materials, such as lead or depleted uranium. Gamma radiation is essentially similar to x-ray radiation, but is usually more energetic (higher frequency on the electromagnetic [EM] spectrum) and nuclear in origin.

A neutron (n) is an uncharged elementary particle with an atomic mass slightly greater than that of a proton. It exists in the nucleus of every atom with the exception of hydrogen-1 (H-1). A free neutron (one that exists outside the nucleus) is unstable and decays with a half-life of about 12 minutes into an electron, proton, and neutrino. Like gamma rays, neutrons are highly penetrating radiations that travel indefinite distances in matter. Neutrons are typically classified according to their kinetic energies (energies associated with movement). These energies are, for the most part, quite arbitrary. Fast neutrons, for example, have kinetic energies on the order of 10 kiloelectron volts (keV) and greater. Slow neutrons have kinetic energies of $\leq$0.5 electron volts (eV). Thermal neutrons, with kinetic energies of 0.025 eV, are a special category of slow neutrons and are considered to be in thermal equilibrium with their surroundings. Fast neutrons are reduced in energy to slow and thermal energies through the use of moderating materials. In contrast to gamma radiation, neutron radiation is conventionally shielded using moderators containing a preponderance of hydrogen atoms and other low Z materials. Examples include paraffin, polyethylene, water, and boron.

Several common characteristics of ionizing radiations are noted in the following table.

Characteristics of Ionizing Radiation

Type	Symbol	Composition	Mass (amu)	Charge	Typical Energies	Range (Air)	Range (Tissue)	Primary Hazard	Examples
Alpha Particle	α	2p + 2n	4	+2	4 - 8 MeV	few centimeters	50 to 70 micrometers	internal	uranium, radon, plutonium
Beta Particle	β	electron	0.00055	± 1	.018 - 3 MeV	up to a few meters	few millimeters	external and internal	strontium-90, carbon-14, tritium
Gamma Ray	γ	electro-magnetic ray	0	0	0.1 - 2 MeV	indefinite	indefinite	external and internal	cobalt-60, cesium-137
X-Ray	x	electro-magnetic ray	0	0	.01 - 150 keV	indefinite	indefinite	external and internal	x-ray machines
Neutron	n	neutron	1	0	0.025 eV - 15 MeV	indefinite	indefinite	external and internal	reactors, neutron sources

Alpha particles, beta particles, gamma rays (photons), and neutrons interact with matter in a number of different ways. These interactions can be grouped into three main categories: charged-particle interactions, photon interactions, and neutron interactions.

Charged-Particle Interactions

When a charged particle (e.g., an alpha or beta particle) moves through matter, it has the potential to interact with hundreds to tens of thousands of atoms. In effect, charged particles are almost in a continuous state of interaction with the matter around them. There are three principal types of interactions:

- Ionization - A process that occurs when an incident charged particle transfers sufficient energy to an orbital electron to completely remove it from the atom.

- Excitation - A process that occurs when an incident charged particle transfers sufficient energy to an orbital electron to raise it to a higher energy state, but does not transfer enough energy to completely remove it from the atom.

- Bremsstrahlung ("braking radiation") - An interaction involving the emission of photon (x-ray) radiation as a result of a deflection in the path of a charged particle due to its interaction with an atomic nucleus.

Alpha radiation consists of fairly massive particles (helium nuclei) emitted from a nucleus with discrete (monoenergetic) energies in the range of 4 to 8 MeV. The kinetic energy of an alpha particle is diminished rapidly through the direct ionization of as many as 40,000 to 80,000 electrons per centimeter traveled. Excitation of atomic electrons is the second principal interaction.

Unlike alpha particles, beta particles are not emitted with discrete energies, but follow a continuous energy distribution. In other words, beta particles are emitted from a particular radionuclide with energies ranging from zero to some maximum value. The maximum energy for a specific beta emitter is typically cited; this value can be found in various places in the literature and is characteristic of the radionuclide. Beta particles lose energy in a number of ways as they pass through matter; ionization and excitation are the most frequent mechanisms. Because of their light mass (the mass of an electron), beta particles do not nearly ionize to the same degree as alpha radiation. For example, for every centimeter of matter traversed, only about 45 electrons are ejected by a beta particle through the ionization process.

The fraction of energy emitted as bremsstrahlung through beta interactions with atomic nuclei is directly related (proportional) to the atomic number of the shielding material and the energy of the beta particle. Therefore, higher beta energies combined with higher atomic-numbered materials increases the occurrence and intensity of bremsstrahlung radiation. The fact that a charged-particle radiation can initiate the emission of penetrating bremsstrahlung (x-ray) radiation requires consideration of appropriate shielding. Beta sources should be shielded first with a low Z material (such as plastic) followed by a high Z material (such as lead). In this way, any penetrating radiation produced by beta interactions in the shield can be attenuated to a large degree by the higher density material. Otherwise, individuals working with and around beta sources could be exposed unnecessarily to photon radiation.

Positron (β^+) sources are unique because they represent the presence of antimatter. In addition to interacting by ionization, excitation, and bremsstrahlung, positrons search for free negative electrons and undergo a process known as annihilation. The positive and negative beta particles collide and are annihilated; mass is converted into energy in the form of two 511 keV annihilation photons. These photons are a source of external radiation exposure.

Photon Interactions

Photons interact with matter in several ways. The two principal characteristics that influence the type of interaction are the energy of the photon and the atomic number (Z) of the material in which the photon interaction takes place. Please note that the origin of the photon is of no importance. Although the photons being discussed in this section are called gamma rays, interactions involving x-rays, bremsstrahlung, and annihilation radiation apply as well.

Gamma rays undergo three types of interactions:

- Photoelectric effect - A mechanism in which all the energy of an x-ray or gamma ray photon is transferred to an atomic electron, which is then ejected from the atom. In the photoelectric effect, the gamma ray photon interacts with a tightly bound electron (an electron found close to the nucleus), transferring essentially all of its energy to the electron. The gamma ray disappears while the electron is ejected from the atom. The interaction is favored for lower energy gamma rays interacting with higher Z materials.

- Compton effect - A mechanism in which a gamma ray photon, with energy $E_{\gamma,}$ interacts with a "free" (loosely bound) outer shell electron and transfers kinetic energy to the electron. In this interaction, the incident gamma ray does not disappear, but instead scatters with degraded energy ($E_\gamma^{/}$); the remainder is imparted to the electron. This interaction occurs with photons over a wide energy range (1 to 10 MeV) and has no strong dependence on atomic number.

  The Compton effect can be represented equationally by:

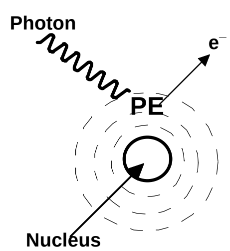
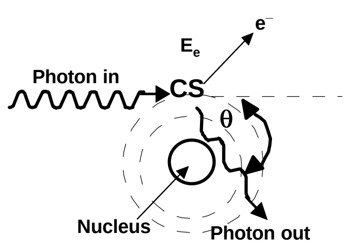
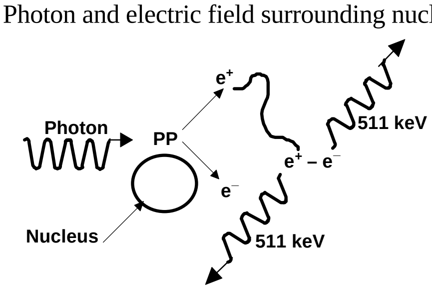
$$E_\gamma^{/} = \frac{E_\gamma}{1 + [(\frac{E_\gamma}{511})(1 - \cos\theta)]}$$

  where:
  $E_\gamma^{/}$ = the energy of the scattered gamma ray (keV)
  $E\gamma$ = the incident (initial) gamma ray energy (keV)
  θ = the scattering angle

- Pair production - A mechanism that illustrates the transformation of energy into mass. In this interaction, a gamma ray, located in the vicinity of an atomic nucleus, completely disappears, and in its place a pair of oppositely charged particles (an electron-positron pair) is created. Even though these particles are of equal mass, the kinetic energy is not necessarily evenly divided between them. This interaction is favored for higher Z materials and is only possible for gamma rays with energies greater than, 1022 keV.

A summary of the major photon interactions with matter can be found in the following table.

Summary of Principle X-Ray and Gamma Ray Photon Interactions

Effect	Interaction Mechanism	Result of Interaction	Dominant Photon Energy Range and Approximate Relationship to E	Dominant Atomic No. (Z) Range and Approximate Relationship to Z
Photoelectric effect	Photon and bound electron (K or L shell) 	Complete absorption of photon energy and emission of electron.	Low energy (<1 MeV)	Most likely to occur with high Z material. Interaction probability increases dramatically with increase in Z (Z^4 power).
Compton scattering or Compton effect	Photon and free electron 	Partial absorption of photon energy. Emission of electron and lower energy photon.	Intermediate energy (1 - 10 MeV)	Interaction probability does not change significantly with a change in Z.
Pair production	Photon and electric field surrounding nucleus 	Complete absorption of photon energy and production of electron-position pair.	High energy (> 10 MeV)	Most likely to occur with high Z material. Interaction probability increases approximately with the square of the atomic number (Z^2 power).

Neutron Interactions

Neutrons do not behave in the same manner as charged-particle (α^{++}, β^{-}) or photon (γ, x) radiations. Neutrons are uncharged particles and cannot directly cause ionization. Therefore, a neutron must either physically interact with an atomic nucleus or come so close to the nucleus as to involve the atom's nuclear forces. Neutrons undergo several unique interactions that can be generally classified as either scattering reactions in which the neutron is still present following the interaction (though with degraded energy) or capture reactions where the neutron is captured by the nucleus, resulting in the emission of both charged and uncharged radiations. Examples of specific interactions include:

- Elastic scattering - This is the most common neutron interaction at any energy. In this reaction, the neutron physically interacts with a target nucleus, initially having no kinetic energy of its own, and imparts kinetic energy to it. The collision causes the incident neutron to scatter. This reaction is considered "elastic" if **total kinetic energy is conserved** (the kinetic energies before and after the collision are equal). For example, like a cue ball hitting a cue ball.

  Equationally, this may be represented by:

  $$E_n = E_T + E_n^{/}$$

  where:

  $E_n^{/}$ = the kinetic energy of the neutron prior to the collision
  E_T = the kinetic energy imparted to the target (recoil) nucleus
  E'_n = the kinetic energy of the scattered neutron

  This reaction is often compared to the collision of two billiard balls. Because they have equal masses, it is possible for maximum energy transfer to occur during a head-on collision. For this reason, materials rich in the element hydrogen (an element with a mass approximating that of a neutron) are best for slowing down neutrons by elastic scattering.

- Inelastic scattering - In this reaction, unlike the previous case, the neutron scatters "inelastically", (i.e., **total kinetic energy is not conserved)**. The nucleus absorbs energy internally and is left in an excited state. In theoretical discussions, the incident neutron is described as being momentarily captured by the target and then subsequently reemitted as a scattered neutron. Simultaneously, a gamma photon is released whose energy is equal to that absorbed internally by the nucleus. Inelastic scattering is energetically possible only for fast neutrons and is favored for heavy (high Z) nuclei. For example, like a cue ball hitting a bowling ball.

Equationally, this may be represented by:

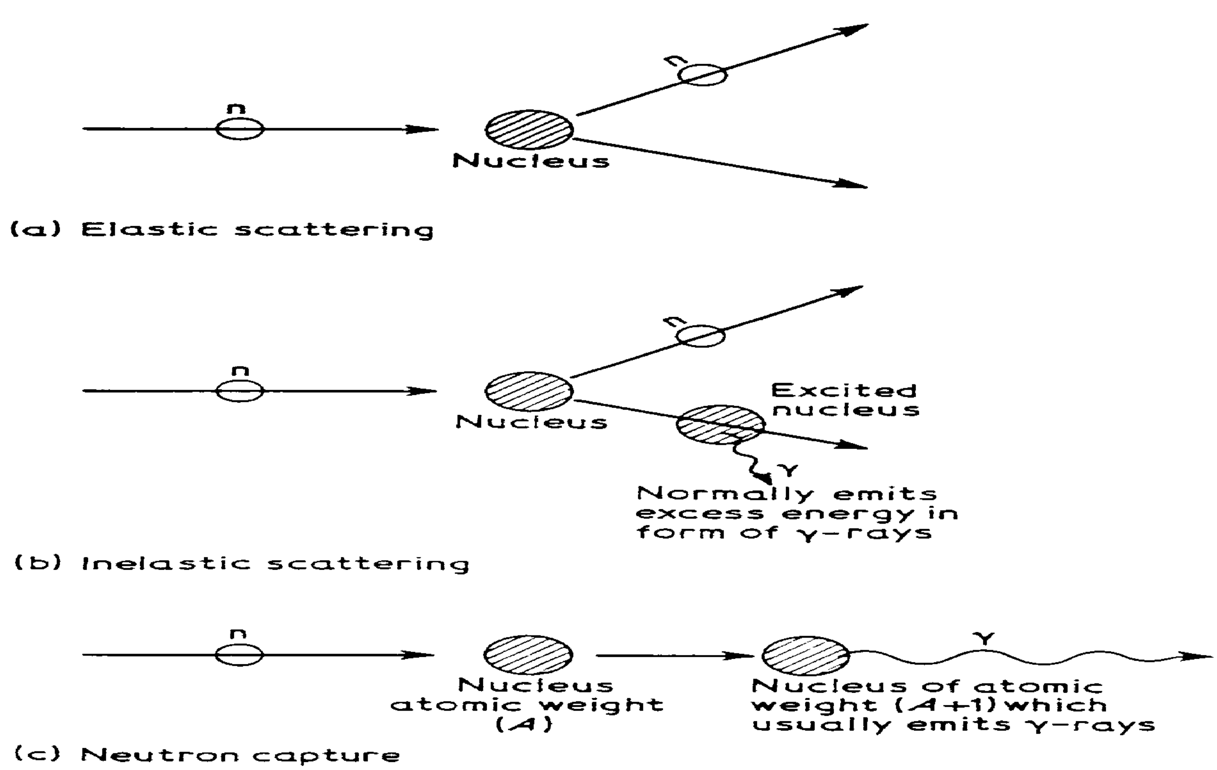
$$E_n = E_T + E_n^{/} + E_\gamma$$

where:

E_γ = a gamma photon whose energy is equal to that absorbed internally by the nucleus

- Capture processes - In contrast to scattering reactions where the neutron interacts with a target nucleus and is subsequently re-emitted with degraded energy, capture reactions involve the actual capture (absorption) of the electrically neutral neutron as it penetrates the coulomb barrier of the atomic nucleus. Once the neutron is captured, a variety of reactions can occur, resulting in the emission of a photon or the ejection of a charged particle.

The three main neutron reactions.



3. SELF-STUDY SCENARIOS/ACTIVITIES AND SOLUTIONS

Activity 1

Calculate the energy of a cesium-137 (662 keV) gamma ray following Compton scattering with an electron at an angle of 180^o.

____

____

____

____

____

____

Activity 2

A neutron with an initial kinetic energy of 10 keV collides with a target nucleus. The neutron then elastically scatters with a kinetic energy of 6 keV. What is the kinetic energy of the recoil nucleus?

____

____

____

____

____

____

____

Activity 3

A fast neutron with a kinetic energy of 5 MeV scatters inelastically with a target nucleus. The nucleus recoils with a kinetic energy of 0.4 MeV and emits a 0.2 MeV gamma ray. What is the energy of the scattered neutron?

Activity 1, Solution

$$E_{\gamma}^{/} = \frac{662}{1 + [(\frac{662}{511})(1 - \cos 180^{0})]}$$

$$E_{\gamma}^{/} = \textbf{184.3 keV}$$

Activity 2, Solution

$E_T = E_n - E_n^{/}$

E_T = 10 keV - 6 keV = **4 keV**

Activity 3, Solution

$E_n^{/} = E_n - E_T - E_{\gamma}$

$E_n^{/}$ = 5 MeV - 0.4 MeV - 0.2 MeV = **4.4 MeV**

4. SUGGESTED ADDITIONAL READINGS AND/OR COURSES

Readings

- Argonne National Laboratory. (1988). *Department of Energy Operational Health Physics Training* (ANL-88-26). Argonne, IL.
- Cember, Herman. (1996). *Introduction to Health Physics* (3rd ed.). McGraw-Hill: New York.
- Gollnick, Daniel A. (1991). *Basic Radiation Protection Technology* (2nd ed.). Pacific Radiation Corporation: Altadena, CA.

Courses

- *Nuclear Physics/Radiation Monitoring* -- DOE.
- DOE/EH-0450 (Revision 0), *Radiological Assessors Training (for Auditors and Inspectors) - Fundamental Radiological Control,* sponsored by the Office of Defense Programs, DOE.
- *Applied Health Physics* -- Oak Ridge Institute for Science and Education.
- *Health Physics for the Industrial Hygienist* -- Oak Ridge Institute for Science and Education.
- *Radiological Worker Training* -- DOE-EH.
- *Radiological Control Technician* -- DOE-EH.
- *Safe Use of Radionuclides* -- Oak Ridge Institute for Science and Education.
- *Radiation Protection General Technical Base Qualification Standard Training* -- GTS Duratek.